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Liquid Hydrogen Fuel System for Small Unmanned Air Vehicles

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Small electric unmanned air vehicles are often considered limited by the low endurance of several hours, mainly set by the energy of their battery energy storage system. The Naval Research Laboratory has been extending the duration of electric UAVs through the use of hydrogen fuel cells, which take advantage of both the high energy of H_2 fuel in combination with the high efficiency (~50%) of polymer fuel cells. In this paper, we describe a project to demonstrate the 3-day flight of NRL's 35-lb Ion Tiger UAV on liquid hydrogen (LH2) fuel. The use of LH2 on a small UAV is complicated because of the limited weight and volume budget, plus the extensive insulation required to keep the LH2 in its cryogenic state (20K) for multiple days, plus match the variable H_2 demand of the fuel cell under flight conditions. A compact, lightweight LH2 flight vessel was successfully designed and built with the aid of extensive thermal modeling. The system performs well in flight and is on track to deliver a 3-day flight. We also discuss issues related to LH2 handling and transportation. While LH2 systems are complex, they can provide unprecedented flight duration for small UAVs.

I. Nomenclature

LH2	=	liquid hydrogen
GH2	=	gaseous hydrogen
LN2	=	liquid nitrogen
H_2	=	hydrogen
O_2	=	oxygen
H_2O	=	water
W	=	Watt
DOT	=	U.S. Department of Transportation

II. Introduction

Extending the flight endurance of small, electric unmanned air vehicles (UAVs) is a goal for designers of both military and commercial systems. Electric propulsion has numerous attractive attributes including near silent operation, instant starting, increased reliability, ease of power control, reduced thermal signature, and reduced vibration. There is no need for a generator and payloads can be operated directly from the propulsion system. The main disadvantage of electric propulsion has been the low capacity, or endurance, of the traditional battery electric power source. We are striving to overcome the limits of low endurance by developing lightweight hydrogen fuel cell propulsion systems for UAVs. Hydrogen fuel cells produce electricity directly by the electrochemical conversion of H_2 and O_2 to H_2O, while taking advantage of the high specific energy of H_2 fuel – 33,410 Wh/kg – for extended endurance.

The Naval Research Laboratory (NRL) first demonstrated fuel cell flight of a remote piloted air vehicle with a 3 hour and 19 minute flight on the 6-pound Spider Lion in 2004.[1] In 2009, we demonstrated 26-hours of electric flight on the fuel cell powered Ion Tiger UAV.[2,3] The Ion Tiger weighed 35 pounds, which included 5-pounds for a payload. The electric propulsion plant comprised a hydrogen fuel cell system, built by Protonex Technology Corporation, which weighed 2.5 lbs and produced a maximum of 550-W. The average vehicle cruise power was about 300-W, where the fuel cell system was about 50% efficient. The required 1.1 pounds of hydrogen fuel was stored at 5000 psi in a 9-pound carbon overwrapped aluminum pressure vessel, with a lightweight single stage regulator, for a total hydrogen storage weight of 12%. The vehicle additionally included an aluminum radiator sized for heat rejection up to 120 °F ambient temperatures. The total weight of the fuel cell system, fuel and radiator was

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14. ABSTRACT
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less than 15 pounds – for the same weight of battery, only about 4 hours of flight would be possible. This leap in technology from Spider Lion to Ion Tiger was enabled both through improvements in fuel cell technology, along with increased knowledge with the fabrication of GH2 pressure vessels.

NRL has been pursuing extending the flight time of Ion Tiger to 3-day missions by using cryogenic hydrogen fuel (i.e., liquid hydrogen or LH2). LH2 has been used in aerospace,[4] and for automotive applications in the United States and Germany.[5] Hydrogen has the highest amount of energy per unit mass (Wh/kg),[6] and can be used in combination with a ~50% efficient polymer fuel cell system for long endurance systems. LH2 has the additional benefit of 3 times energy per unit volume (Wh/L) compared to gaseous H_2 stored at 5000 psi. The higher density means that about 3x the weight of LH2 can be stored for about the same volume as 5000 psi gaseous H_2. Another major benefit of LH2 is that it can be stored near 50 psi vs. the 5000 to 10000 psi typical for compressed hydrogen. The lower storage pressure of LH2 eliminates the need for a heavy carbon-overwrapped pressure vessel and permits lighter weight storage vessels, improving its specific energy at a system level.[7] However, LH2 has unique storage requirements and is challenging to store in small volumes. The LH2 must be kept near 20 K, so an appropriate high-quality insulation jacket must be used. The insulation must be designed for the appropriate amount of LH2 boil off (or evaporation) to the gas phase, to be fed as H_2 gas to the fuel cell system. We also developed a methodology for fueling smaller systems.

This paper summarizes our present work towards the use of LH2 in a small UAV, to achieve an unprecedented goal of 3-days of flight. The experimentation and flight testing give insight into the practicality of LH2 flight systems.

III. Liquid Hydrogen System and Design

A. LH2 Flight Vessel Concept

We imposed several design goals and constraints so that we could make a good comparison to flying a UAV on gaseous vs. liquid H_2. First, the fuel tank and regulator must weigh no more than the 3.7 kg 5000-psi GH2 tanks developed for Ion Tiger and fit in the existing vehicle fuselage. It also must be able to supply H2 at the appropriate rate for cruise and full power. The appropriate flow rates for Ion Tiger are given in Table 1.[8]

Table I: H_2 flow rates for Ion Tiger. The target flow rates for the LH2 flight vessel are in yellow.

Fuel Flow Rate Requirements				
Phase	Duration	Duration [s]	Flow Rate [g/min]	Flow Rate [g/s]
Warm Up	10 min	600	0.05	8.33E-04
Climb Out	15 min	900	0.70	1.17E-02
Cruise	71.3 hr	256680	0.34	5.67E-03
Landing	15 min	900	0.05	8.33E-04

Beyond that, our challenge was to take advantage of the 3x higher density of LH2, so we planned to carry 1.5 kg of LH2, or 3x the amount in the 5000-psi gaseous H2 tank that was flown for 26-h. To effectively use this 1.5 kg of LH2, the tank must be able to conserve the LH2 well over 3 days, and thus have low H2 permeability and only boil off H2 that is consumed in flight. Additionally the tank requires practical features, such as filling and vent ports, plus pressure relief valves.

We opted to pursue nested aluminum vessels, separated by a layer of vacuum insulation. A conceptual schematic of our LH2 vacuum flask, or dewar, is shown in Figure 1, along with a photograph of a prototype dewar. It resembles one developed for the automotive industry,[7~~5~~] and a similar tank construction has been examined by NASA for flight on long-endurance UAVs.[9] Aluminum was selected for both the inner and outer walls of the LH2 dewar because of its low H2 permeability, lightweight, and high strength.

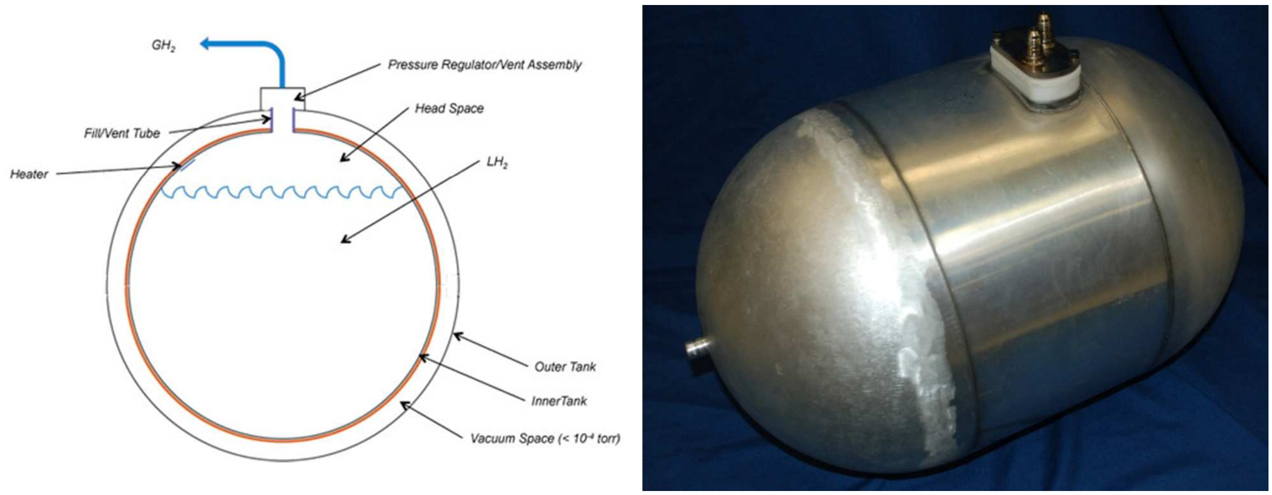

Figure 1. Liquid hydrogen flight dewar for Ion Tiger. (left) schematic of cross section of conceptual dewar, (right) prototype aluminum dewar with the fueling interface.

Another method to reduce LH2 boil off is through the use of a recooling system,[5]~~[3]~~ but the continuous LH2 boil off needed for flight, combined with the weight and volume penalty for a recooling system, made this approach less attractive.

B. Designing the Hydrogen Leak Rate of the Storage Vessel

The heat leak of the system must be designed carefully to control hydrogen boil off, or the hydrogen flow rate. For maximal use of the LH2 in the tank, the boil off rate of the LH2 must match the consumption by the fuel cell. Boil-off rate faster than the fuel cell consumption leads to an overpressure in the tank resulting in venting unspent fuel. Boil-off rate slower than the fuel cell consumption requires spending energy heating the LH2 to produce gas. The latter is preferred, but is achieved with extra insulation and thus tank weight. The heat leak required for the H_2 flow rates in Table I, are summarized in Table II. As we discussed in our prior work for GH2[2]~~[1]~~ the H_2 flow must be sufficient to fly for extended periods of time at high power, specifically for take off, and also to stay aloft in strong head winds. The minimum flow rate presents a challenge as well, because lower H_2 flow rates require more insulation to keep the LH2 from boiling off.

Heat Transfer Rates to Satisfy Fuel Flow Rates		
	Vaporize the LH_2 Heat Transfer Rate [W]	Warm up the GH_2 Heat Transfer Rate [W]
Warm Up	0.34	3.0
Climb Out	4.78	41.4
Cruise	2.32	20.1
Landing	0.34	3.0

Table II: Heat transfer rates needed to boil off LH2 and meet H_2 flow rates for the fuel cell. Design targets for the LH2 flight dewar are highlighted in yellow.

A model was developed for the dewar with vacuum insulation to account for thermal losses through conduction, radiation and convection for the selected surface area of the dewar. More details of this model are published elsewhere.[8]~~[6]~~ The modeling showed that the most effective means to maintain adequate flow for high power was to have “headroom” or a gaseous volume, above the LH2 in the dewar, which could be used on demand when higher H_2 flow rates were needed. GH2 in the headroom either flows to the fuel cell to be consumed, or some pressure is built up if the fuel cell H_2 consumption is lower than the boil off rate. If the pressure exceeds about 60 psi, it is blown off through a safety valve, to maintain a sufficient safety factor for the aluminum pressure vessel and to minimize heat transfer to the LH2. The models showed that to minimize the headroom and keep the dewar volume compact, a low-power heater is needed to provide extra H_2 flow for extended high power operation. The models were proven in a lab-scale demonstration system with liquid nitrogen.

C. Liquid Hydrogen Fueling

An additional challenge with using LH2 is logistics, as specialized equipment is needed for storage prior to flights. NRL set up on site a 1000-L Linde LH2 storage vessel, originally developed for the demonstration of fuel cell automobiles with LH2 fuel. The storage dewar is designed to be filled by commercial vendor, in this case Air Products (Figure 2). The 1000-L dewar is situated on a concrete pad, and has a 25-foot stand off distance to non-spark-resistant electronics, per the National Fire Protection Association (NFPA) regulations for cryogenic fluids.[3] For this volume of LH2, standard handling procedures require users to wear non-static, flame-resistant clothing, such as NOMEX®, and only use spark-proof tools.

Figure 2. 1000-liter liquid hydrogen dewar at NRL being fueled by a commercial vendor.

For flight testing, the LH2 is transferred from the 1000-L dewar to a DOT-certified 100-L dewar from CryoFab using a flex hose with the Linde dewar hose fitting. The 100-L dewar is transported to the flight range in a DOT-certified open-bed truck, with a HAZMAT-certified driver. The use of the 100-L dewar is made somewhat easier, because the relatively low volume of LH2 does not present the same hazards as the 1000-L volumes, and thus the NFPA regulations are less restrictive. Full safety precautions are still rigorously followed and the LH2 is only handled outdoors to ensure maximal ventilation.

At the flight range, the Ion Tiger LH2 dewar is first cooled down to about 77K with liquid nitrogen (LN2). While not compulsory, precooling with LN2 allows conservation of the more expensive LH2, as the cryogenic liquid will boil off rapidly until the dewar temperature is at equilibrium. The LH2 is decanted, and then the air vehicle dewar is fueled with LH2 from the 100-L LH2 dewar. Again, more LH2 boils off until the dewar and cryogenic liquid are at equilibrium – a process that can take several hours in the highly insulated dewar. As the tank is filled, it is weighed to determine the amount of LH2 that has been added. Typically, we fuel the flight dewar a day in advance of the planned flight test to ensure equilibrium, and then top off the tank just before flight.

During fueling, the Ion Tiger is held in a custom stand with strain gauges to measure the amount of LH2 in the tank. After fueling, the Ion Tiger is handled the same as the one with gaseous hydrogen.

IV. Flight Testing

The system was ground checked to confirm that the GH2 coming from the LH2 system had no adverse effect on the fuel cell system. The regulated GH2 entering the fuel cell is at approximately ambient temperature, so there are minimal differences between GH2 and LH2 downstream of the pressure regulator. Flight testing the system is crucial as LH2 systems are sensitive to many conditions in flight that cannot be fully tested on the ground, such as sloshing from the movement of the vehicle and during banking and inclines. Further, while the impact of cooling from air flow would ordinarily be tested in a wind tunnel, LH2 safety complicates indoor testing in a wind tunnel, as infrastructure, such as spark-proof lighting, H_2 sensors, etc., are required for maximal safety. For an experimental system for which the leak rates are not fully known, outdoor testing is most expedient, with flight testing the true indicator of performance.

Preliminary test flights show that the NRL LH2 design works well for the Ion Tiger. Results from a 170-minute flight test are show in Figure 3. The data shows the heater in the LH2 vessel comes on and off to meet respective increases and decreases in flight power as the vehicle is purposely exercised. Not shown are the fuel cell results, which showed that the Protonex fuel cell system operated normally at the same efficiency (~50%) as measured with GH2 operation. As the heater turns on (bottom), the tank pressure increases from the build up of GH2. When the heater turns off, the tank pressure drops as the GH2 is consumed. Finally, near 60 psi at 160 minutes of flight, the blow off valve for the tank works properly, ensuring that an overpressure of GH2 does not form.

At the time of the submission of this paper, we had completed a successful 8-h flight test of the Ion Tiger with the LH2 tank described herein, and were on track to complete 72-h flights.

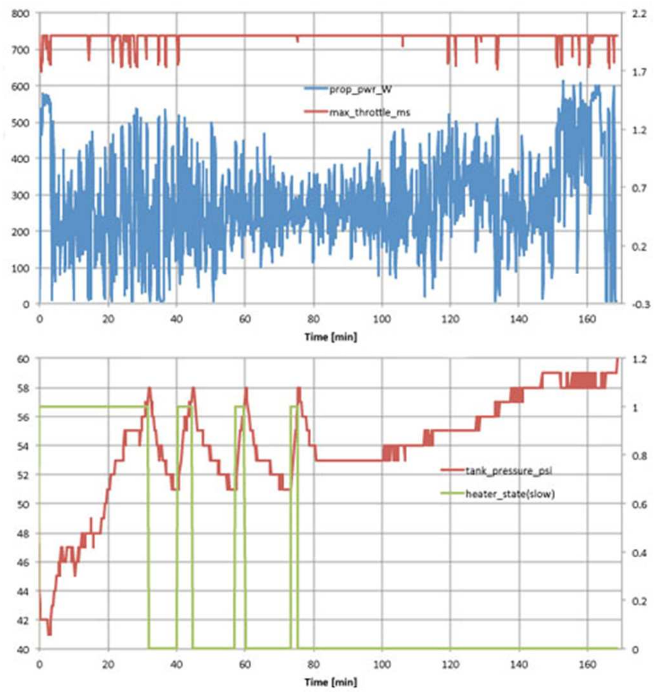

Figure 3. Flight testing results from Ion Tiger flying with a LH2 vessel and powered by a hydrogen fuel cell. (top) power to propellor; (bottom) heater in LH2 system turning on and off, and associated pressure of GH2 in the vessel.

V. Conclusions

From our first 3 hr and 19 minute demonstration of the Spider Lion in 2004 to these multi-day flights of the Ion Tiger in 2012, hydrogen fuel cell technology has clearly improved, along with our knowledge of hydrogen fueling systems. Efficient fuel cell propulsion combined with high energy LH2 in a lightweight storage vessel provides an unprecedented opportunity to achieve multiday flights in a small, 35-lb UAV. The LH2 flight vessel design is far more challenging than for GH2, and extensive modeling of the thermal insulation system is required. Additionally, careful design is required to build a light weight compact tank. The insulation must be able to hold a very low heat leak on the order of 2 to 4 W, and be supplemented with a heater to match the variable GH2 demand of the fuel cell system in practical conditions. The transportation and handling of LH2 is well understood, but certainly requires special conditions and safety precautions.

Now that the technical feasibility of such systems has been demonstrated, the determining factor for the use of LH2 systems will be whether it makes economic sense to build the systems and the required infrastructure. For instance, is the cost of a LH2 infrastructure, handling, and flight vessels offset by the 3x reduction in takeoff and landing cycles? Alternatively, how does the cost of a small, 35-lb UAV compare with that of large long-range systems in terms of capability? Other determining factors, such as the available infrastructure and the mission, are likely deciding factors. Nonetheless, hydrogen fuel cell technology provides a clear path to achieving long endurance flights.

VI. Acknowledgments

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